Lecture 13

MOSFET Differential Amplifiers

topics

- Ideal characteristics of differential amplifier
  - Input differential resistance
  - Input common-mode resistance
  - Differential voltage gain
  - CMRR
- Non-ideal characteristics of differential amplifier
  - Input offset voltage
  - Input biasing and offset current
- Differential Amplifier with active load
- Frequency response

MOS differential pair

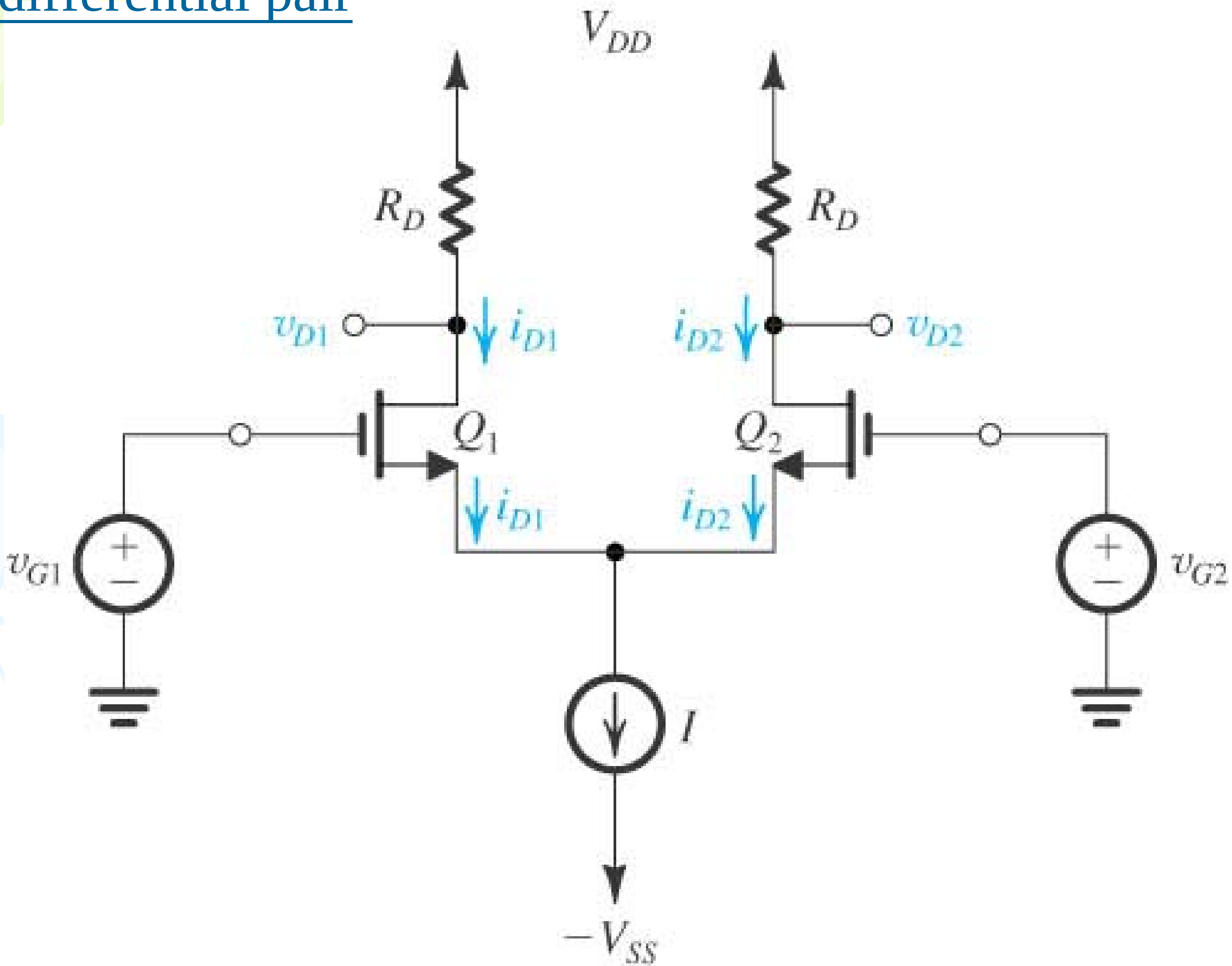


Figure 7.1 The basic MOS differential-pair configuration.

Common mode operation

BJT's differential pair V_{CM} no bound

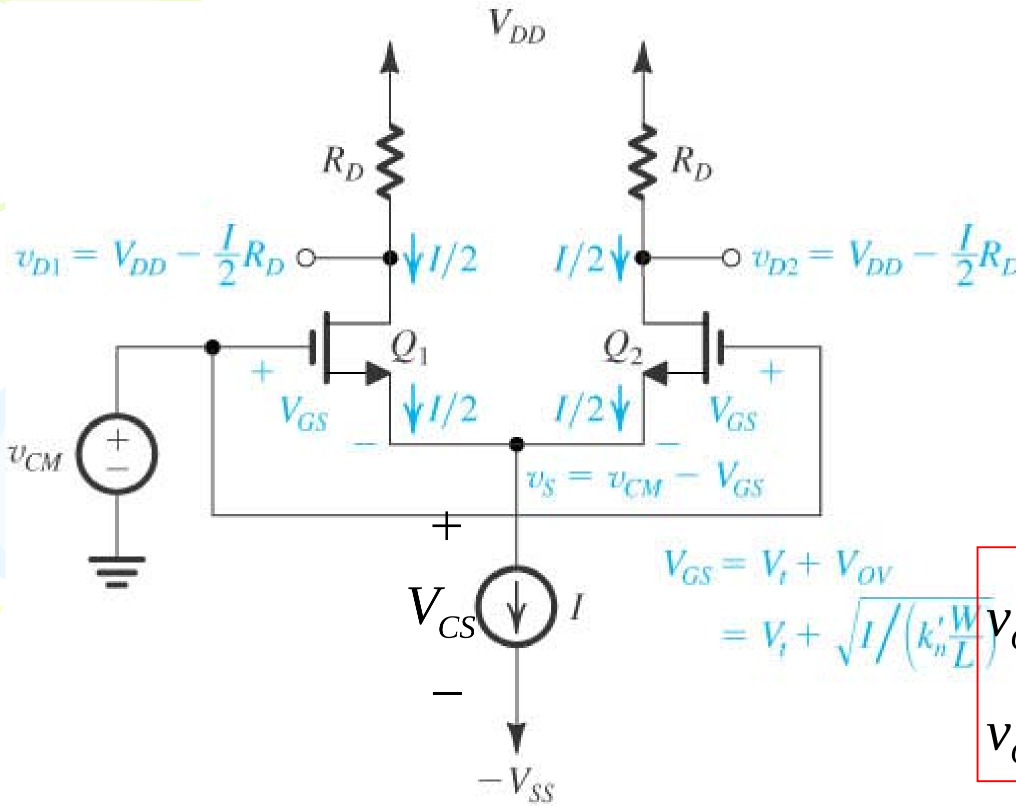


Figure 7.2 The MOS differential pair with a common-mode input voltage v_{CM}.

$$\because Q_1 = Q_2$$

$$\therefore I_{D1} = I_{D2} = \frac{I}{2}$$

$$v_s = v_{CM} - V_{GS}$$

$$I_D = \frac{I}{2} = \frac{1}{2} k_n^{'} \frac{W}{L} (V_{GS} - V_t)^2$$

$$v_{D1} = v_{D2} = V_{DD} - I_D R_D$$

Q_1 and Q_2 in saturation mode

$$v_{DS} > v_{GS} - V_t$$

$$(V_{DD} - I_D R_D) - v_S > v_{CM} - v_s - V_t$$

$$\boxed{\begin{aligned} v_{CM\,(\max)} &= V_t + V_{DD} - \frac{I}{2} R_D \\ v_{CM\,(\min)} &= -V_{ss} + V_{CS} + V_t + (V_{GS} - V_t) \end{aligned}}$$

$$v_{GS} - V_t = v_{CM} - v_s - V_t$$

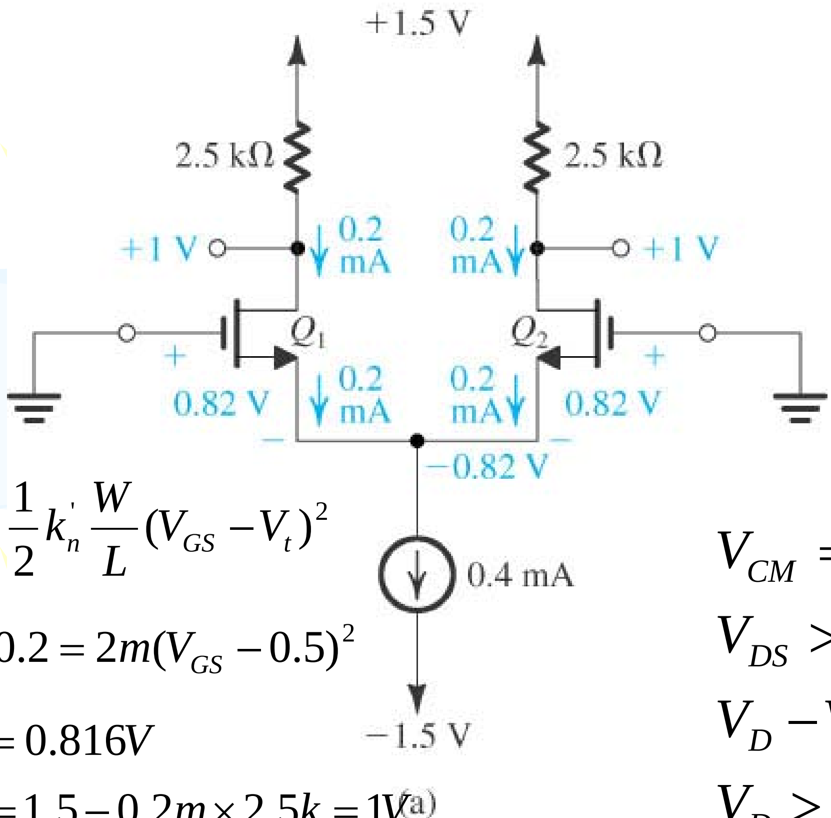
$$= v_{CM} - (V_{CS} - V_{SS}) - V_t$$

$$v_{CM} = V_{CS} - V_{SS} + v_{GS}$$

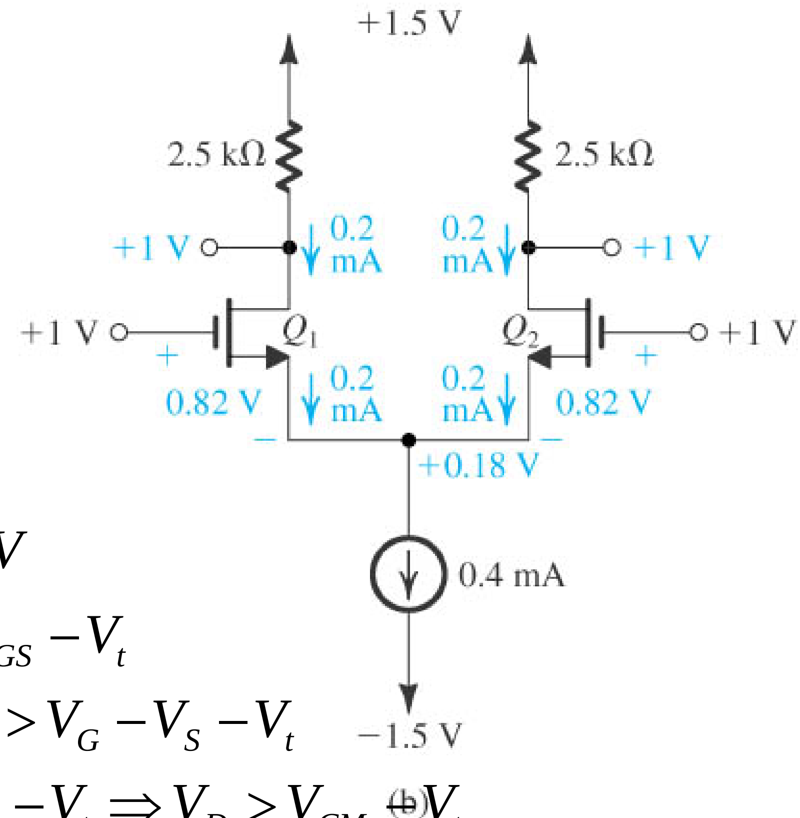
Make sure current source is working

Exercise 7.1

$$V_{DD} = V_{SS} = 1.5V, k_n^{'} \frac{W}{L} = 4mA/V^2, V_t = 0.5V, I = 0.4mA, R_D = 2.5k$$



(a)



(b)

$$I_D = \frac{1}{2} k_n^{'} \frac{W}{L} (V_{GS} - V_t)^2$$

$$\frac{I}{2} = 0.2 = 2m(V_{GS} - 0.5)^2$$

$$V_{GS} = 0.816V$$

$$V_{DS} = 1.5 - 0.2m \times 2.5k = 1V$$

$$V_{DS} > V_{GS} - V_t = 0.816 - 0.5$$

Saturation mode

$$V_{CM} = 1V$$

$$V_{DS} > V_{GS} - V_t$$

$$V_D - V_S > V_G - V_S - V_t$$

$$V_D > V_G - V_t \Rightarrow V_D > V_{CM} - V_t$$

$$\Rightarrow V_D = 1 > 1 - 0.5$$

Saturation mode

$$\boxed{V_{CM\,(\max)} = 1.5V}$$

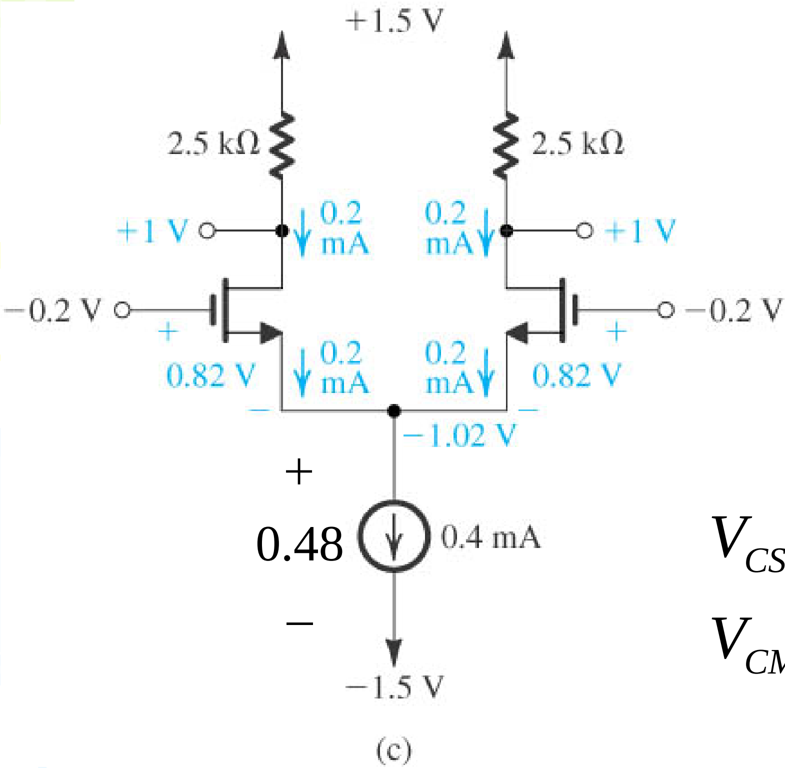


Figure 7.3 *(Continued)*

$$V_{CS\,(\mathrm{min})} = 0.48$$

$$V_{CM\,(\mathrm{min})} = 0.82 + 0.48 - 1.5 = -0.2V$$

Differential mode operation

$$I_{D1} = I = \frac{1}{2} k_n^{'} \frac{W}{L} (V_{GS1} - V_t)^2$$

$$V_{GS1} = V_t + \sqrt{2I / k_n^{'}(W/L)}$$

$$v_{id\,(\max)} = v_{GS1} + v_S = V_t + \sqrt{2I / k_n^{'}(W/L)} - v_{GS2}$$

$$\because Q_2 \quad off \Rightarrow v_{GS2} = V_t$$

$$if \quad v_{id} > v_{id\,\max} \Rightarrow i_{D1} = I$$

$$\Rightarrow v_{GS1} = V_t + \sqrt{2I / k_n^{'}(W/L)}$$

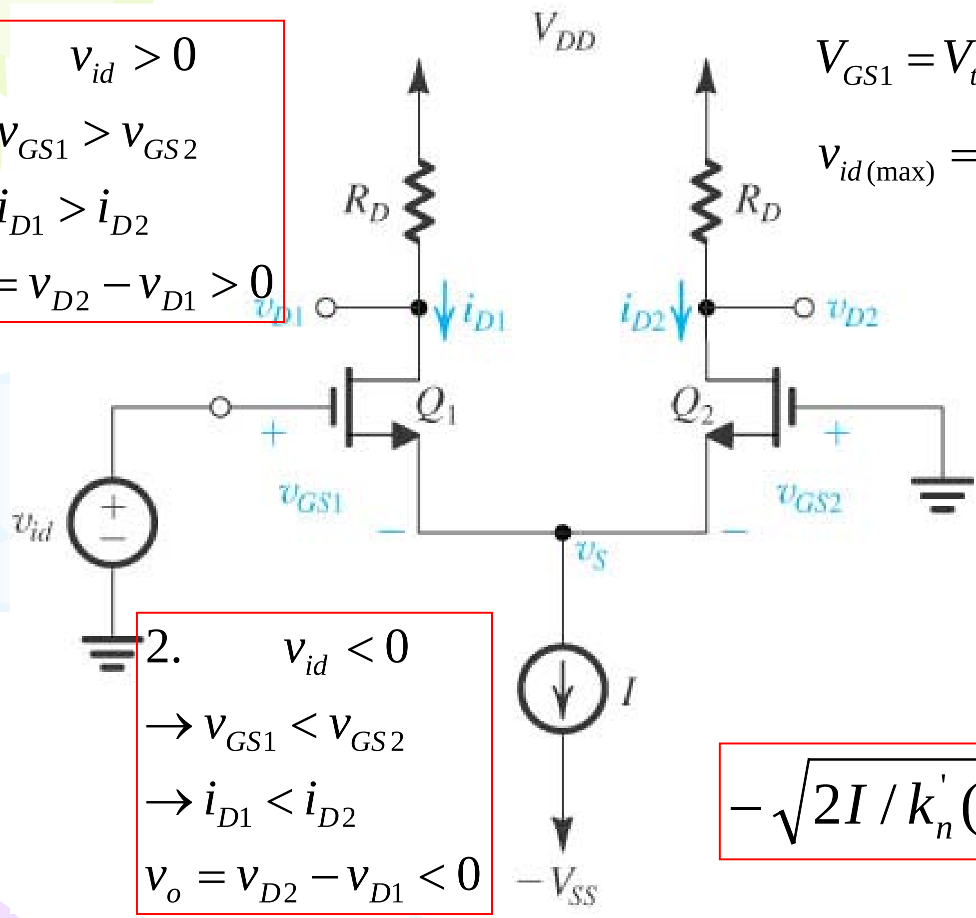
$$v_{id} \uparrow \rightarrow v_s \uparrow \rightarrow Q_2 \Rightarrow \quad off$$

1. $v_{id} > 0$

$\rightarrow v_{GS1} > v_{GS2}$

$\rightarrow i_{D1} > i_{D2}$

$v_o = v_{D2} - v_{D1} > 0$



2. $v_{id} < 0$

$\rightarrow v_{GS1} < v_{GS2}$

$\rightarrow i_{D1} < i_{D2}$

$v_o = v_{D2} - v_{D1} < 0$

$$\boxed{-\sqrt{2I / k_n^{'}(W/L)} \le v_{id} \le \sqrt{2I / k_n^{'}(W/L)}}$$

Figure 7.4 The MOS differential pair with a differential input signal v_{id} applied. With v_{id} positive: $v_{GS1} > v_{GS2}$, $i_{D1} > i_{D2}$, and $v_{D1} < v_{D2}$; thus $(v_{D2} - v_{D1})$ will be positive. With v_{id} negative: $v_{GS1} < v_{GS2}$, $i_{D1} < i_{D2}$, and $v_{D1} > v_{D2}$; thus $(v_{D2} - v_{D1})$ will be negative.

Large signal operation

$$v_{id} = v_{GS1} - v_{GS2} = v_{G1} - v_{G2}$$

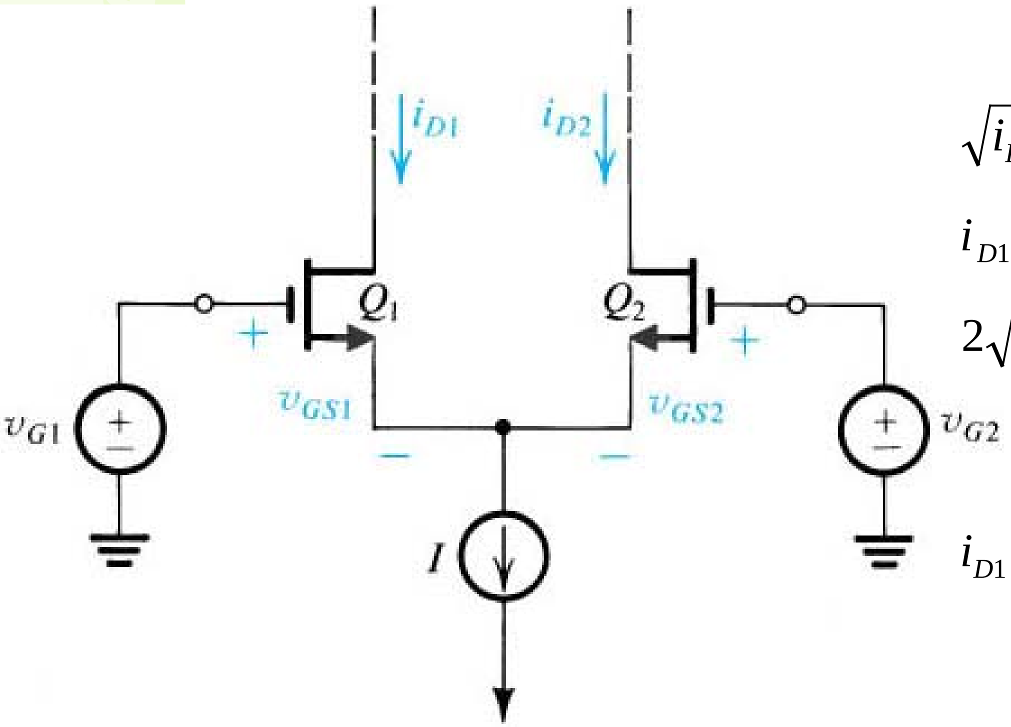


Figure 7.5 The MOSFET differential pair for the purpose of deriving the transfer characteristics, i_{D1} and i_{D2} versus $v_{id} = v_{G1} - v_{G2}$.

$$i_{D1} = \frac{1}{2} k_n^{'} \frac{W}{L} (v_{GS1} - V_t)^2$$

$$i_{D2} = \frac{1}{2} k_n^{'} \frac{W}{L} (v_{GS2} - V_t)^2$$

$$\sqrt{i_{D1}} - \sqrt{i_{D2}} = \sqrt{\frac{1}{2} k_n^{'} \frac{W}{L}} v_{id}$$

$$i_{D1} + i_{D2} = I$$

$$2\sqrt{i_{D!} i_{D2}} = I - \frac{1}{2} k_n^{'} \frac{W}{L} v_{id}^2$$

$$i_{D1} = \frac{I}{2} + \sqrt{\frac{1}{2} k_n^{'} \frac{W}{L} I} \left(\frac{v_{id}}{2}\right) \sqrt{1 - \left(\frac{v_{id}/2}{\sqrt{\frac{1}{2} k_n^{'} \frac{W}{L}}}\right)^2}$$

$$i_{D1} = \frac{I}{2} - \sqrt{\frac{1}{2} k_n^{'} \frac{W}{L} I} \left(\frac{v_{id}}{2}\right) \sqrt{1 - \left(\frac{v_{id}/2}{\sqrt{\frac{1}{2} k_n^{'} \frac{W}{L}}}\right)^2}$$

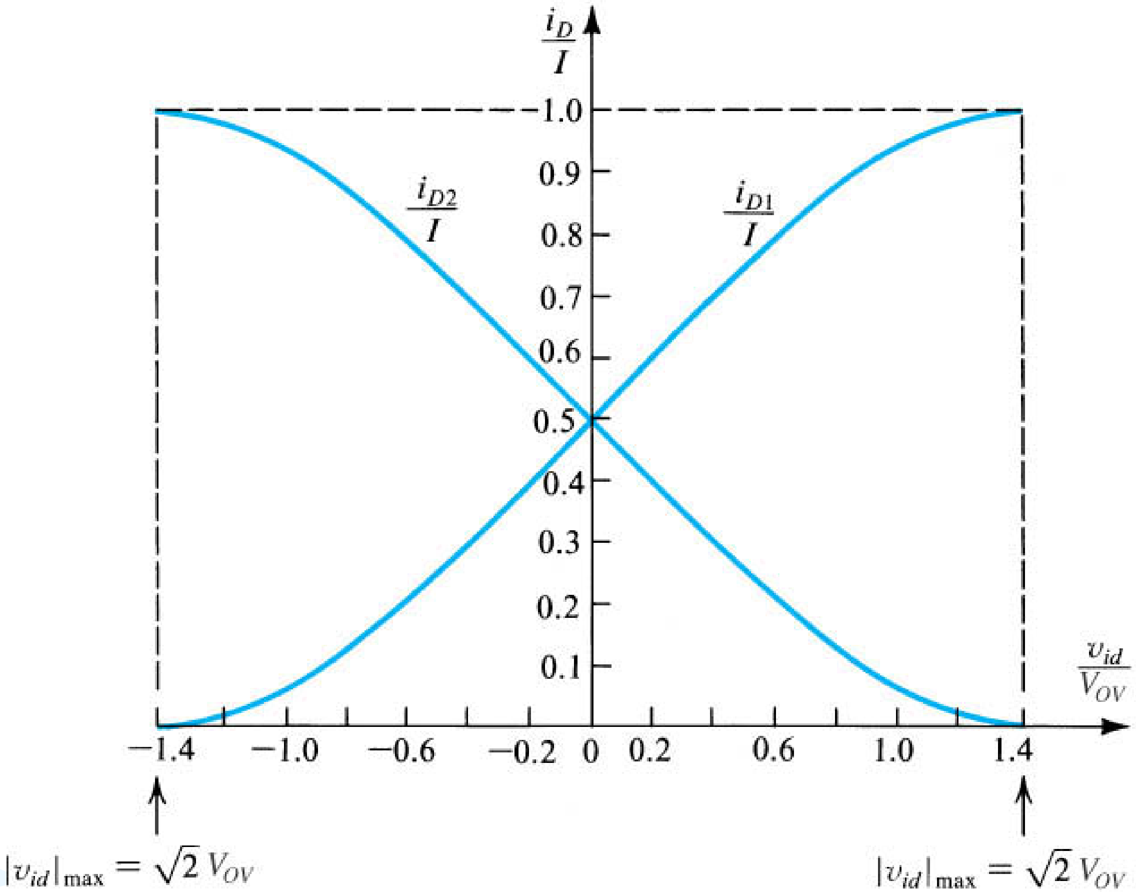


Figure 7.6 Normalized plots of the currents in a MOSFET differential pair. Note that V_{OV} is the overdrive voltage at which Q_1 and Q_2 operate when conducting drain currents equal to $I/2$.

$$i_{D1} = \frac{I}{2} + \sqrt{\frac{1}{2}k_n' \frac{W}{L} I}\left(\frac{v_{id}}{2}\right)\sqrt{1 - \left(\frac{v_{id}/2}{\sqrt{\frac{1}{2}k_n' \frac{W}{L}}}\right)^2}$$

More k is bigger more linear range of v_{id}

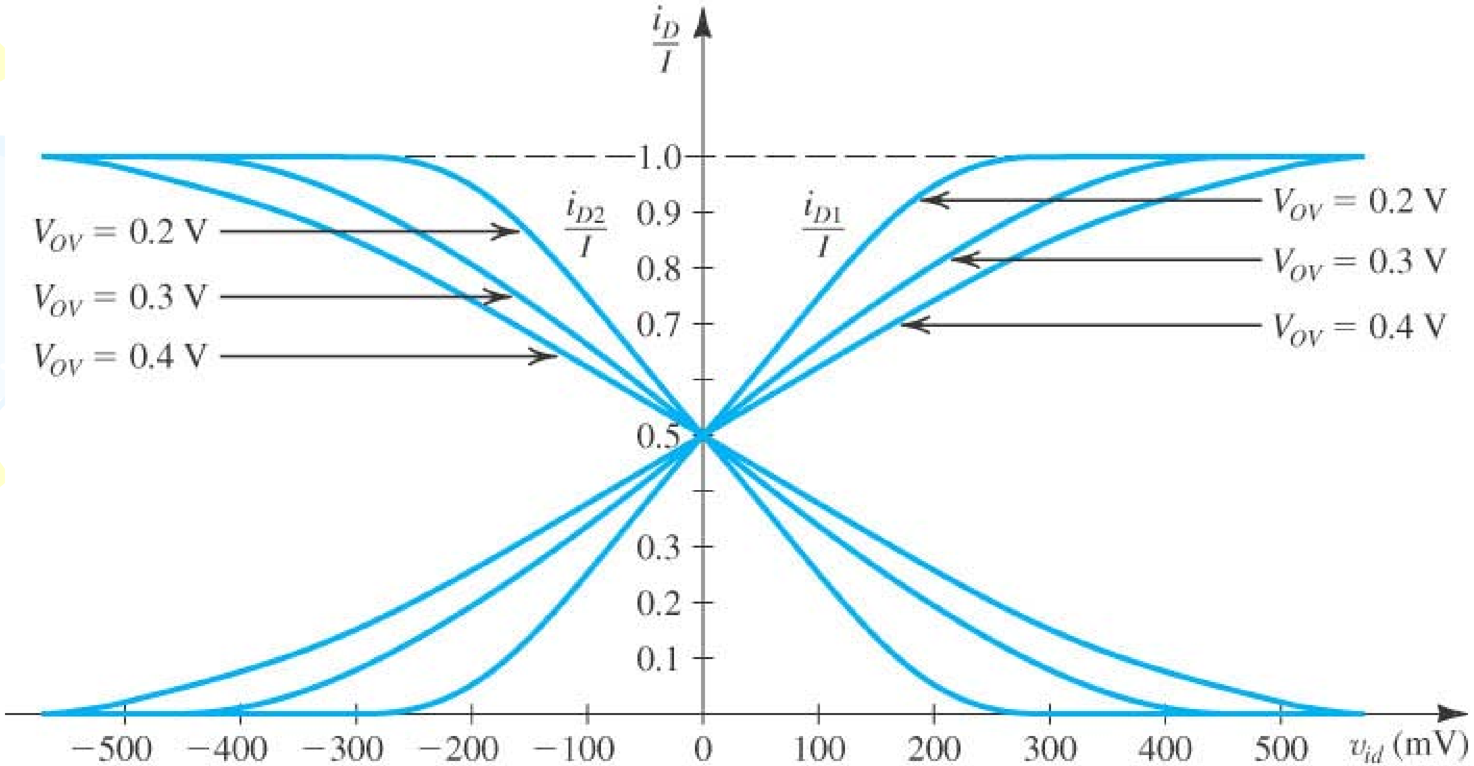


Figure 7.7 The linear range of operation of the MOS differential pair can be extended by operating the transistor at a higher value of V_{OV}.

7-2.1 Small signal operation (differential gain)

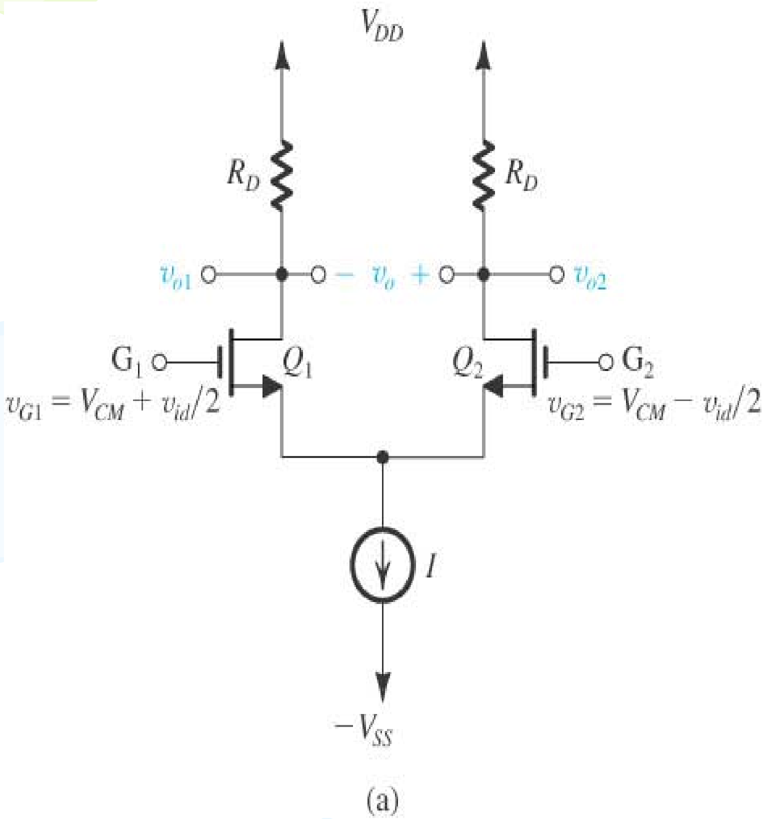


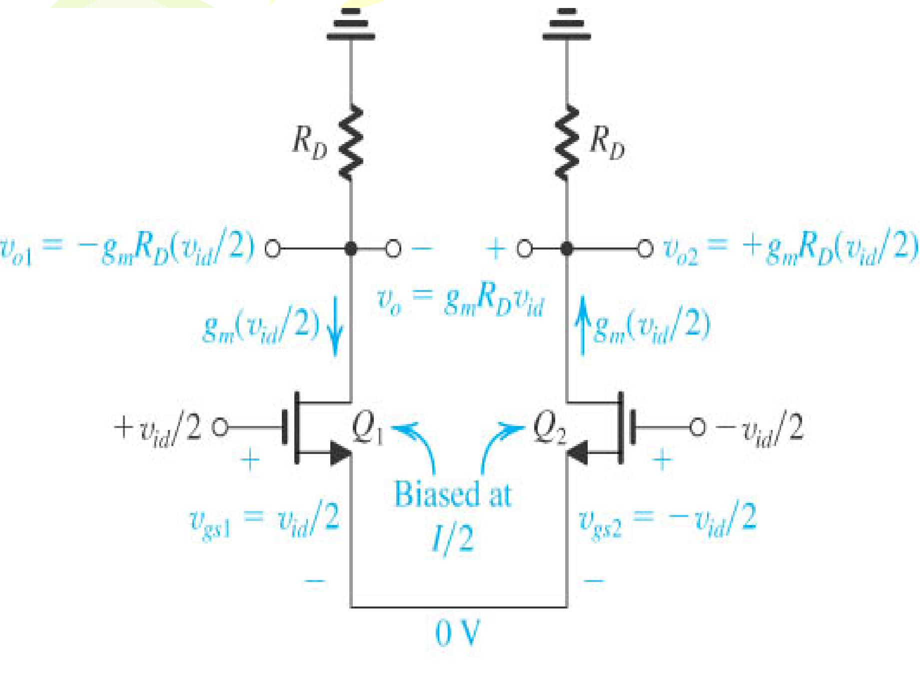
Figure 7.8 Small-signal analysis of the MOS differential amplifier: **(a)** The circuit with a common-mode voltage applied to set the dc bias voltage at the gates and with v_{id} applied in a complementary (or balanced) manner. **(b)** The circuit prepared for small-signal analysis. **(c)** An alternative way of looking at the small-signal operation of the circuit.

$$v_{G1} = v_{CM} + \frac{1}{2} v_{id}$$

$$v_{G2} = v_{CM} - \frac{1}{2} v_{id}$$

$$v_{CM} = \frac{v_1 + v_2}{2}$$

$$v_{id} = \frac{v_1 - v_2}{2}$$



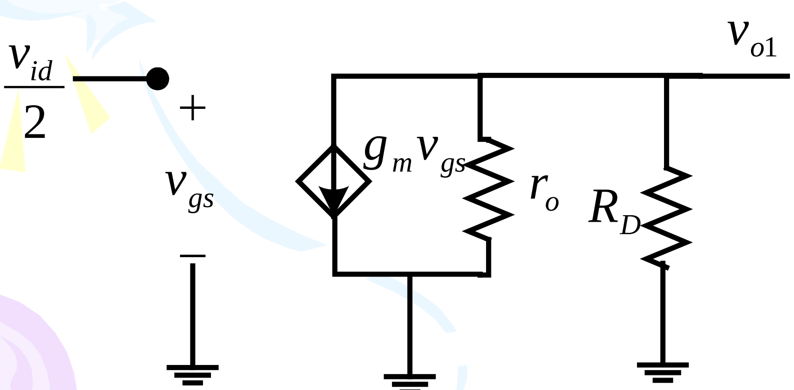
(b)

$$v_{o1} = -g_m \frac{v_{id}}{2}(R_D // r_{o1})$$

$$v_{o2} = g_m \frac{v_{id}}{2}(R_D // r_{o2})$$

$$\frac{v_{o1}}{v_{id}} = -g_m \frac{1}{2}(R_D // r_{o1}), \frac{v_{o2}}{v_{id}} = g_m \frac{1}{2}(R_D // r_{o2})$$

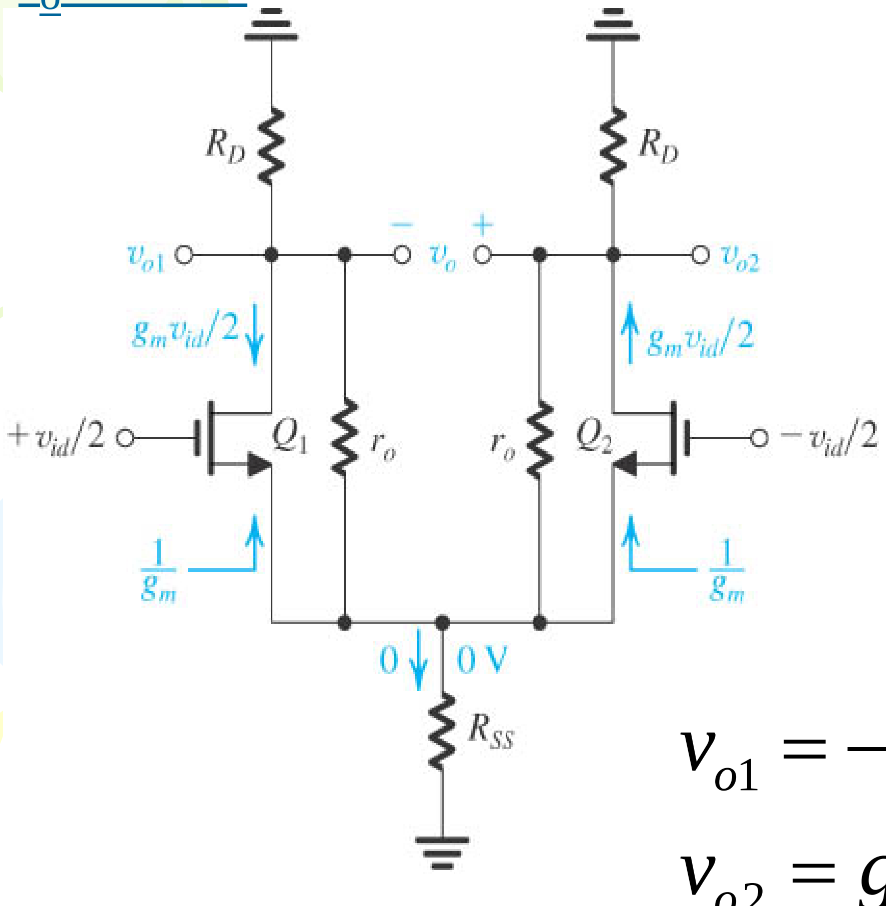
$$A_d \equiv \frac{v_{o2} - v_{o1}}{v_{id}} = g_m(R_D // r_o)$$



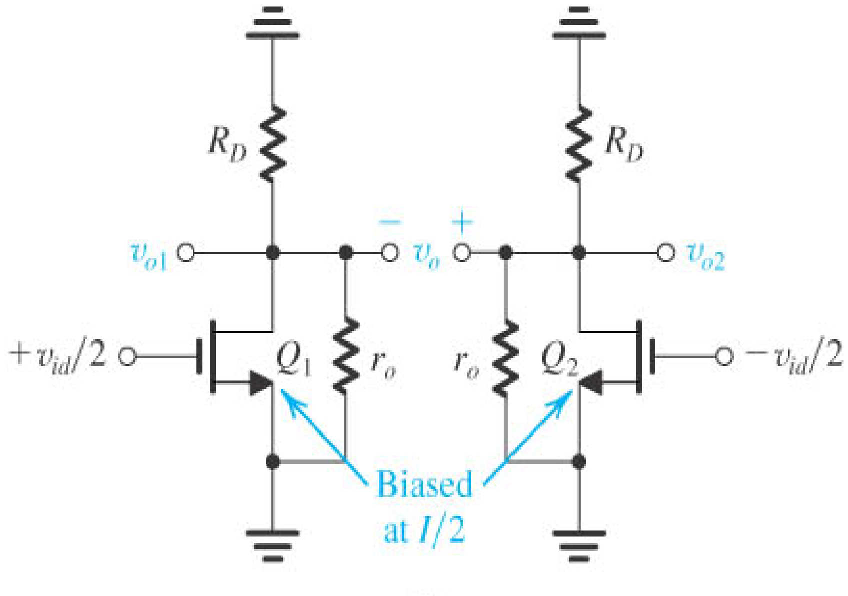
$$R_{id} = \infty$$

$$R_{o\frac{1}{2}} = r_o // R_D$$

r_o effects



(a)



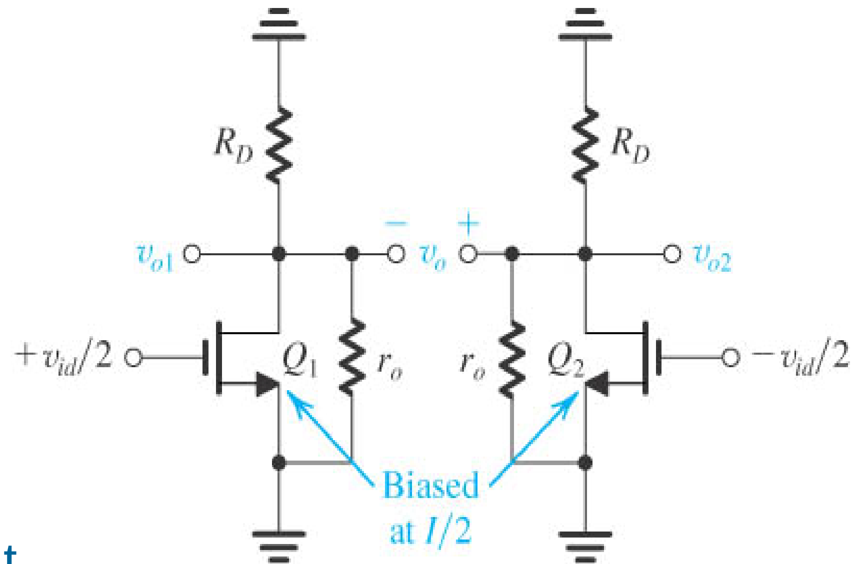
(b)

$$v_{o1} = -g_m(R_D // r_o)(v_{id}/2)$$

$$v_{o2} = g_m(R_D // r_o)(v_{id}/2)$$

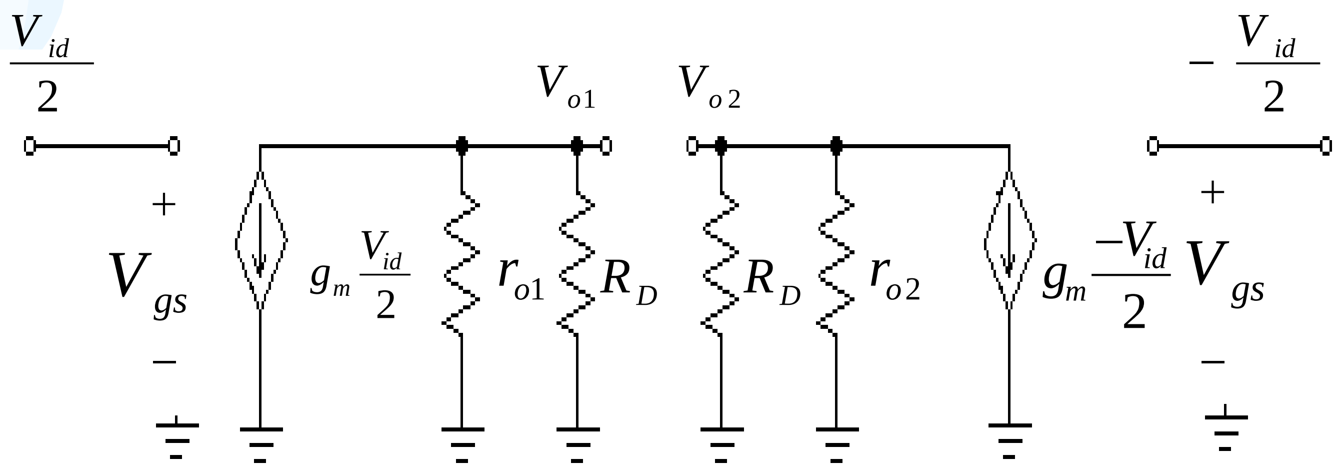
$$v_o = v_{o2} - v_{o1} = g_m(R_D // r_o)v_{id}$$

$$v_{o1} = -g_m(R_D // r_o)(v_{id} / 2)$$
$$v_{o2} = g_m(R_D // r_o)(v_{id} / 2)$$
$$v_o = v_{o2} - v_{o1} = g_m(R_D // r_o)v_{id}$$
$$A_d = \frac{v_{o2} - v_{o1}}{v_{id}} = g_m(R_D // r_o)$$

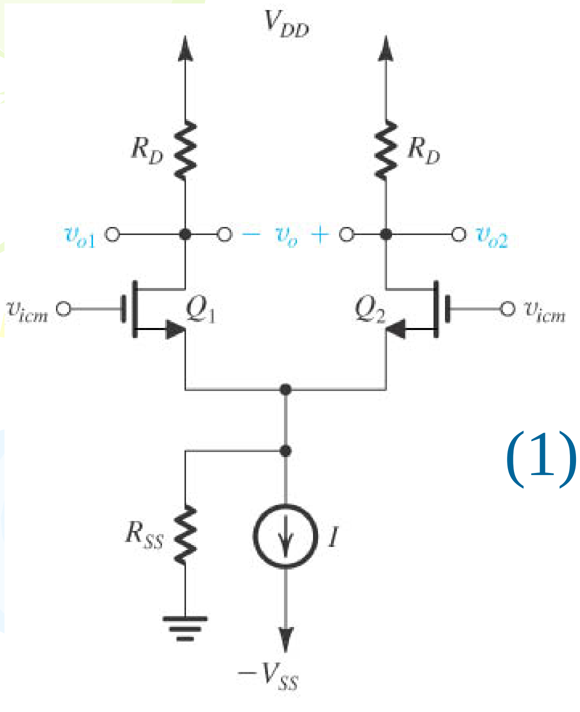


(b)

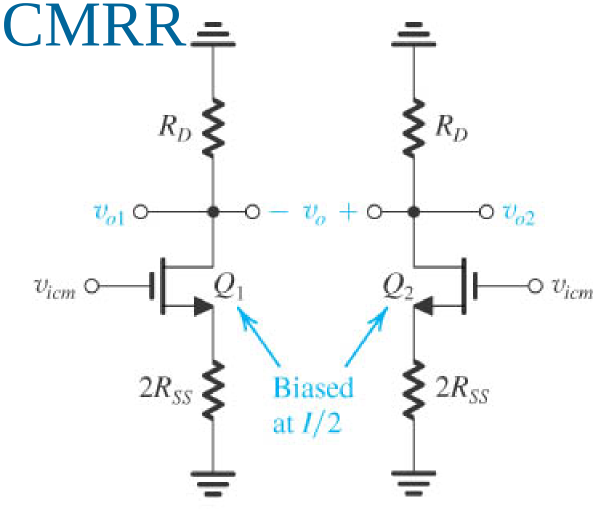
Differential-mode equivalent circuit



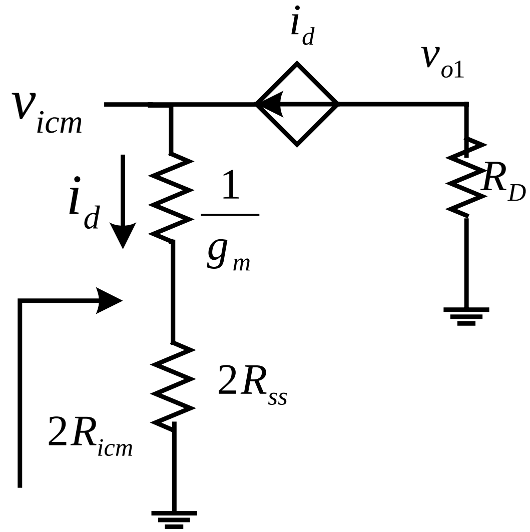
Common-mode gain et CMRR



(a)



(b)



(1) Half circuit of differential pair

$$\left|A_{cm}\right|_{\frac{1}{2}} = R_D / 2R_{ss}, \left|A_d\right|_{\frac{1}{2}} = \frac{1}{2} g_m R_D$$

$$CMRR \equiv \left|\frac{A_d}{A_{cm}}\right| = g_m R_{ss}$$

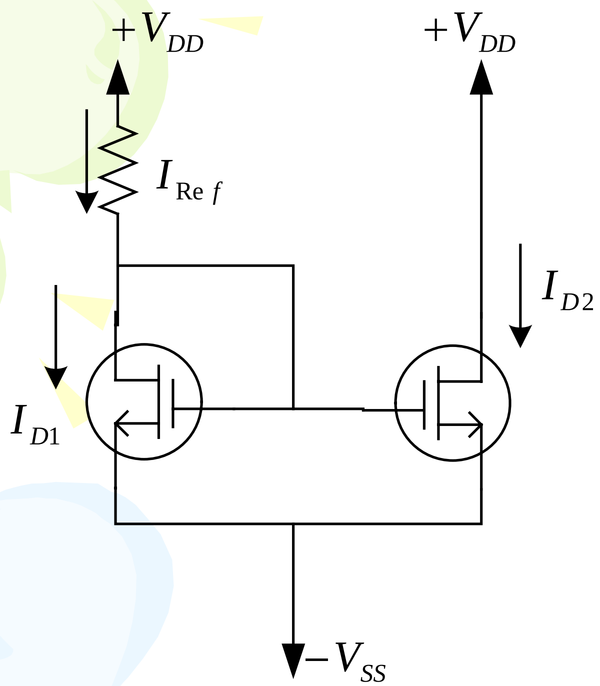
$$\frac{v_{o1}}{v_{icm}} = \frac{v_{o2}}{v_{icm}} = -\frac{R_D}{1/g_m + 2R_{SS}}$$

$$\because R_{SS} >> 1/g_m \Rightarrow \frac{v_{o1}}{v_{icm}} = \frac{v_{o1}}{v_{icm}} = -\frac{R_D}{2R_{SS}}$$

(2) Full circuit

$$\left|A_{cm}\right| = (v_{o2} - v_{o1}) / v_{icm} = 0, \left|A_d\right| = (v_{o2} - v_{o1}) / v_{id} = g_m R_D$$

$$CMRR \equiv \left|\frac{A_d}{A_{cm}}\right| = \infty$$

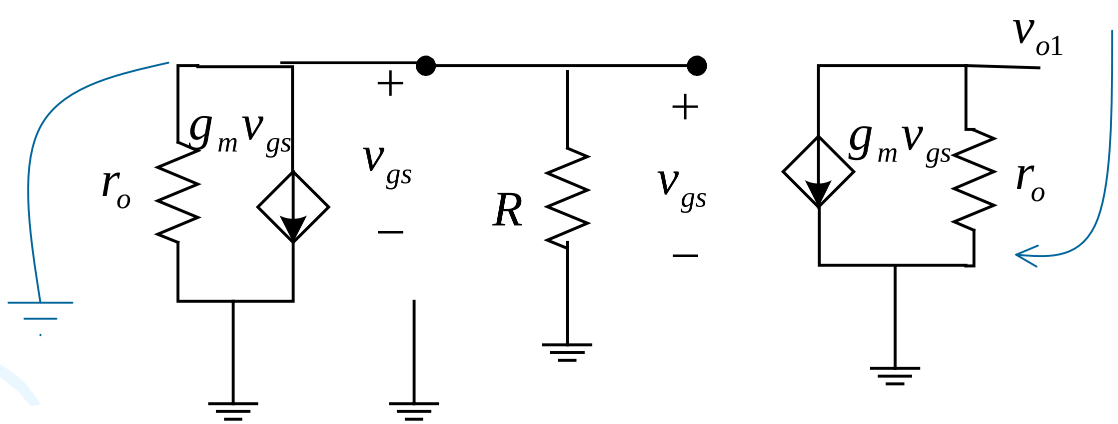


$$I_D = \frac{1}{2} k_n' \frac{W}{L} (v_{GS} - V_t)^2$$

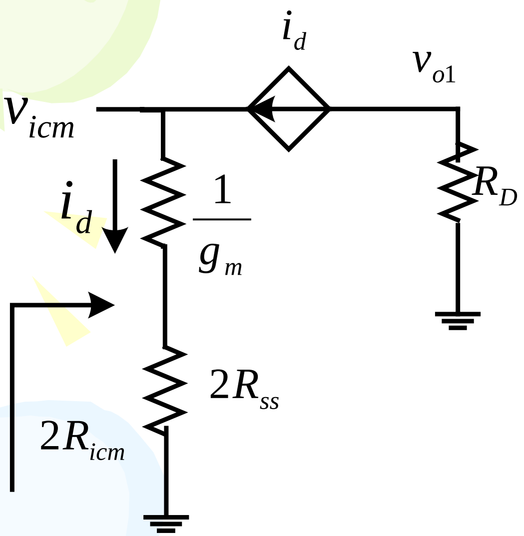
$$v_{GS1} = v_{GS2} \Rightarrow I_{D1} = I_{D2} = I_{ref}$$

$$I_{D1} = \frac{V_{DD} + V_{SS} - V_{GS}}{R}$$

$$\boxed{R_o = r_o = R_{SS}}$$



Non zero common gain due to R_D mismatch



$$\frac{v_{o1}}{v_{icm}} = \frac{v_{o1}}{v_{icm}} = -\frac{R_D}{1/g_m + 2R_{SS}}$$

$$\because R_{SS} >> 1/g_m \Rightarrow \frac{v_{o1}}{v_{icm}} = \frac{v_{o1}}{v_{icm}} = -\frac{R_D}{2R_{SS}}$$

$$consider \quad R_{D1} \neq R_{D2}$$

$$v_{o1} \cong -\frac{R_D}{2R_{ss}} v_{icm}$$

$$v_{o2} \cong -\frac{R_D + \Delta R_D}{2R_{ss}} v_{icm}$$

$$v_{o2} - v_{o1} = -\frac{\Delta R_D}{2R_{ss}} v_{icm}$$

$$A_{cm} = -\frac{\Delta R_D}{2R_{ss}} = -\frac{R_D}{2R_{ss}} \frac{\Delta R_D}{R_D}$$

$$A_d = -g_m R_D$$

$$CMRR \equiv \left| \frac{A_d}{A_{cm}} \right| = 2g_m R_{ss} / \frac{\Delta R_D}{R_D}$$

Non zero common gain due to g_m mismatch

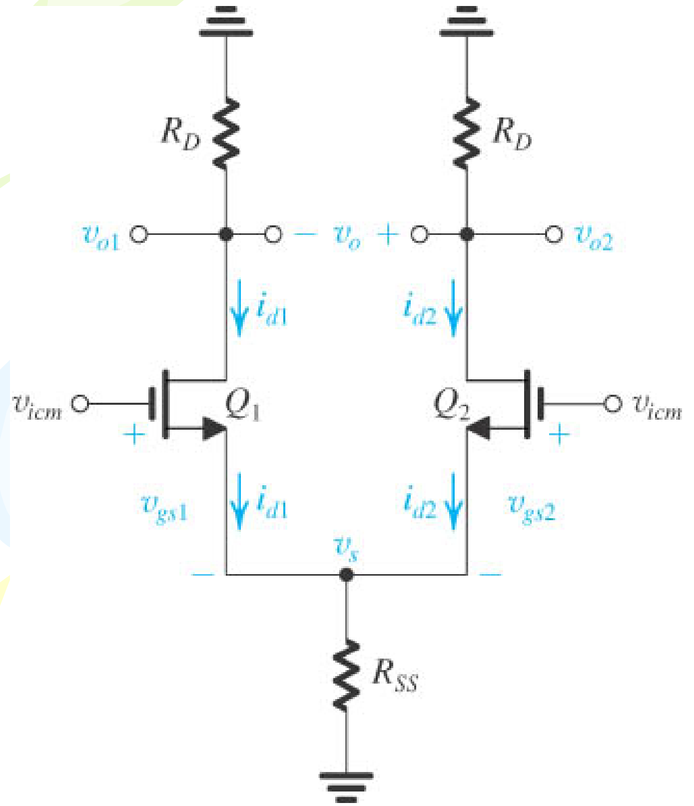


Figure 7.11 Analysis of the MOS differential amplifier to determine the common-mode gain resulting from a mismatch in the g_m values of Q_1 and Q_2.

$$\boxed{\begin{aligned} i_d &= \frac{\mu C_{ox} W}{2L}(v_{gs} - V_t)^2 \\ g_m &= \frac{\mu C_{ox} W}{L}(v_{gs} - V_t) \end{aligned}}$$

$$consider \quad g_{m1} \neq g_{m2}$$

$$\because v_{gs1} = v_{gs2} \Rightarrow \frac{i_{d1}}{i_{d2}} = \frac{g_{m1}}{g_{m2}}$$

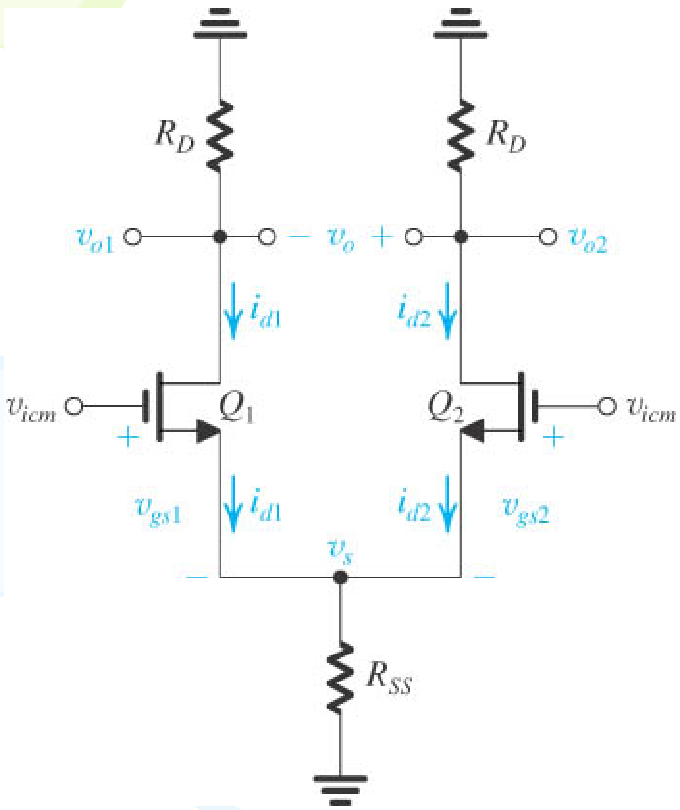
$$v_s = (i_{d1} + i_{d2})R_{ss} \Rightarrow (i_{d1} + i_{d2}) = \frac{v_s}{R_{ss}}$$

$$v_s \approx v_{icm} \Rightarrow (i_{d1} + i_{d2}) = \frac{v_{icm}}{R_{ss}}$$

$$i_{d1} = \frac{g_{m1} v_{icm}}{(g_{m1} + g_{m2})R_{ss}}$$

$$i_{d2} = \frac{g_{m2} v_{icm}}{(g_{m1} + g_{m2})R_{ss}}$$

$$let \quad \Delta g_m = g_{m1} - g_{m2}$$



$$\Rightarrow i_{d1} = \frac{g_{m1} v_{icm}}{2 g_m R_{ss}}$$

$$\Rightarrow i_{d2} = \frac{g_{m2} v_{icm}}{2 g_m R_{ss}}$$

$$v_{o2} - v_{o1} = -i_{d2} R_D + i_{d1} R_D = \frac{\Delta g_m R_D v_{icm}}{2 g_m R_{ss}}$$

$$A_{cm} = \frac{R_D}{R_{ss}} \frac{\Delta g_m}{2 g_m}$$

$$A_d = -g_m R_D$$

$$CMRR \equiv \left| \frac{A_d}{A_{cm}} \right| = 2 g_m R_{ss} / \frac{\Delta g_m}{g_m}$$

Input offset voltage

1. $R_{D1} \neq R_{D2}$
2. $Q_1 \neq Q_2 \qquad \frac{W_1}{L_1} \neq \frac{W_2}{L_2}$
3. $Q_1 \neq Q_2 \qquad V_{t1} \neq V_{t2}$

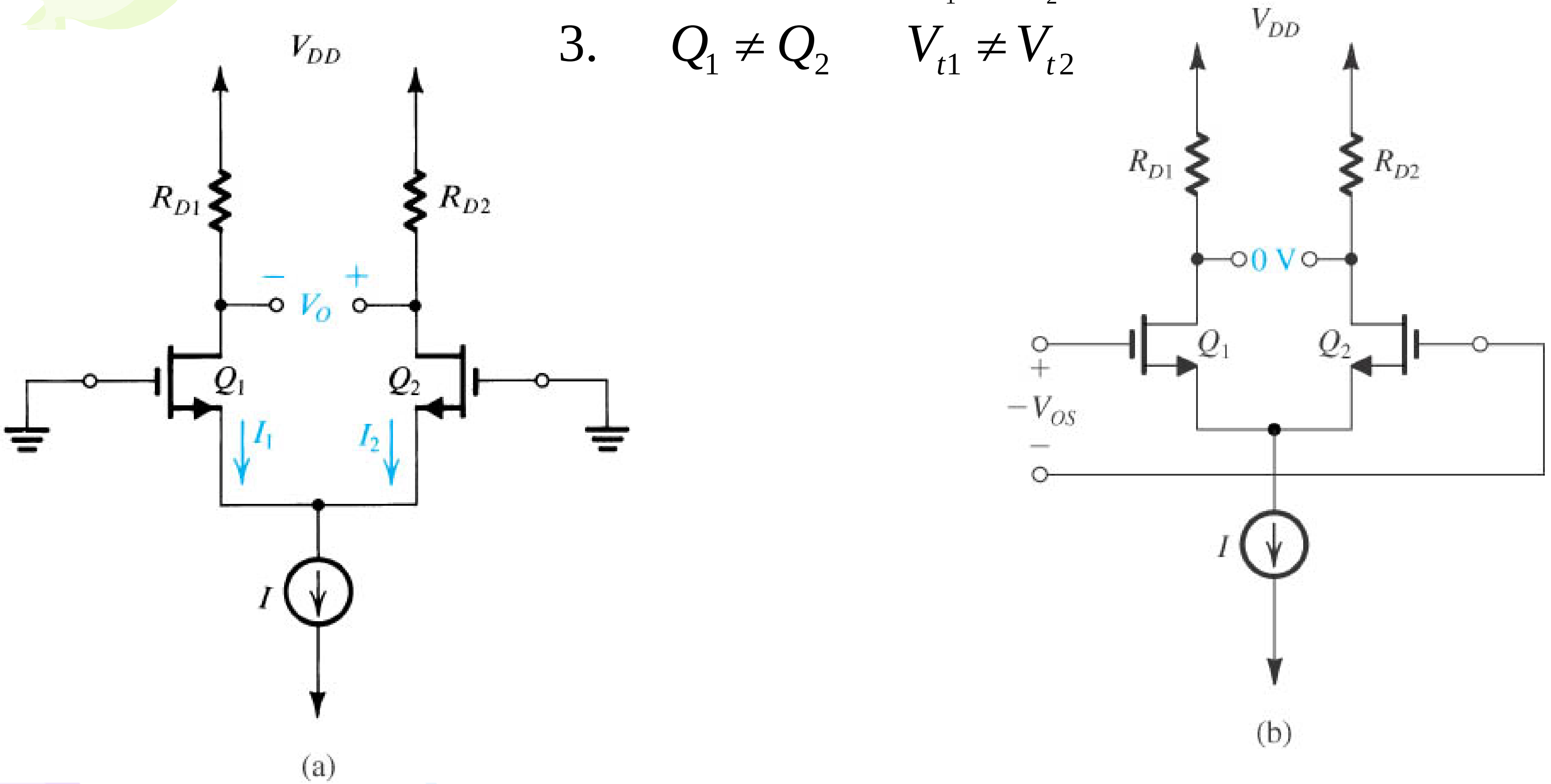


Figure 7.25 (a) The MOS differential pair with both inputs grounded. Owing to device and resistor mismatches, a finite dc output voltage V_O results. **(b)** Application of a voltage equal to the input offset voltage V_{OS} to the terminals with opposite polarity reduces V_O to zero.

$$consider \quad R_{D1} \neq R_{D2}$$

$$R_{D1} = R_D + \frac{\Delta R_D}{2}$$

$$R_{D2} = R_D - \frac{\Delta R_D}{2}$$

$$V_{D1} = V_{DD} - \frac{I}{2}(R_D + \frac{\Delta R_D}{2})$$

$$V_{D2} = V_{DD} - \frac{I}{2}(R_D - \frac{\Delta R_D}{2})$$

$$V_O = V_{D2} - V_{D1} = \frac{I}{2}\Delta R_D$$

$$V_{os} = \frac{V_O}{A_d} = \frac{V_O}{g_m R_D} = \frac{\frac{I}{2}\Delta R_D}{g_m R_D}$$

$$= \frac{\frac{\mu C_{ox} W}{2L}(V_{GS} - V_t)^2}{\frac{\mu C_{ox} W}{L}(V_{GS} - V_t)} \frac{\Delta R_D}{R_D} = \Big(\underbrace{\boxed{\frac{(V_{GS} - V_t)}{2}}}_{V_{oV}}\Big)\Big(\frac{\Delta R_D}{R_D}\Big)$$

$$V_{os} = \Big(\frac{V_{OV}}{2}\Big)\Big(\frac{\Delta R_D}{R_D}\Big)$$

$$consider \quad Q_1 \neq Q_2$$

$$\Big(\frac{W}{L}\Big)_1 = \frac{W}{L} + \frac{1}{2}\Delta\Big(\frac{W}{L}\Big)$$

$$\Big(\frac{W}{L}\Big)_2 = \frac{W}{L} - \frac{1}{2}\Delta\Big(\frac{W}{L}\Big)$$

$$I_1 = \frac{I}{2} + \frac{I}{2}\frac{\Delta(W/L)}{(W/L)}$$

$$I_2 = \frac{I}{2} - \frac{I}{2}\frac{\Delta(W/L)}{(W/L)}$$

$$\Delta I = \frac{I}{2}\frac{\Delta(W/L)}{2(W/L)}$$

$$V_{os} = \Big(\frac{V_{OV}}{2}\Big)\Big(\frac{\Delta(W/L)}{(W/L)}\Big)$$

$consider \quad V_{t1} \neq V_{t2}$

$$V_{t1} = V_t + \frac{\Delta V_t}{2}$$

$$V_{t2} = V_t - \frac{\Delta V_t}{2}$$

$$I_1 = \frac{1}{2} k_n^{'} \frac{W}{L} (V_{GS} - V_t - \frac{\Delta V_t}{2})^2 = \frac{1}{2} k_n^{'} \frac{W}{L} (V_{GS} - V_t)^2 [1 - \frac{\Delta V_t}{2(V_{GS} - V_t)}]^2$$

$$I_1 \approx \frac{1}{2} k_n^{'} \frac{W}{L} (V_{GS} - V_t)^2 (1 - \frac{\Delta V_t}{V_{GS} - V_t})$$

$$I_{12} \approx \frac{1}{2} k_n^{'} \frac{W}{L} (V_{GS} - V_t)^2 (1 + \frac{\Delta V_t}{V_{GS} - V_t})$$

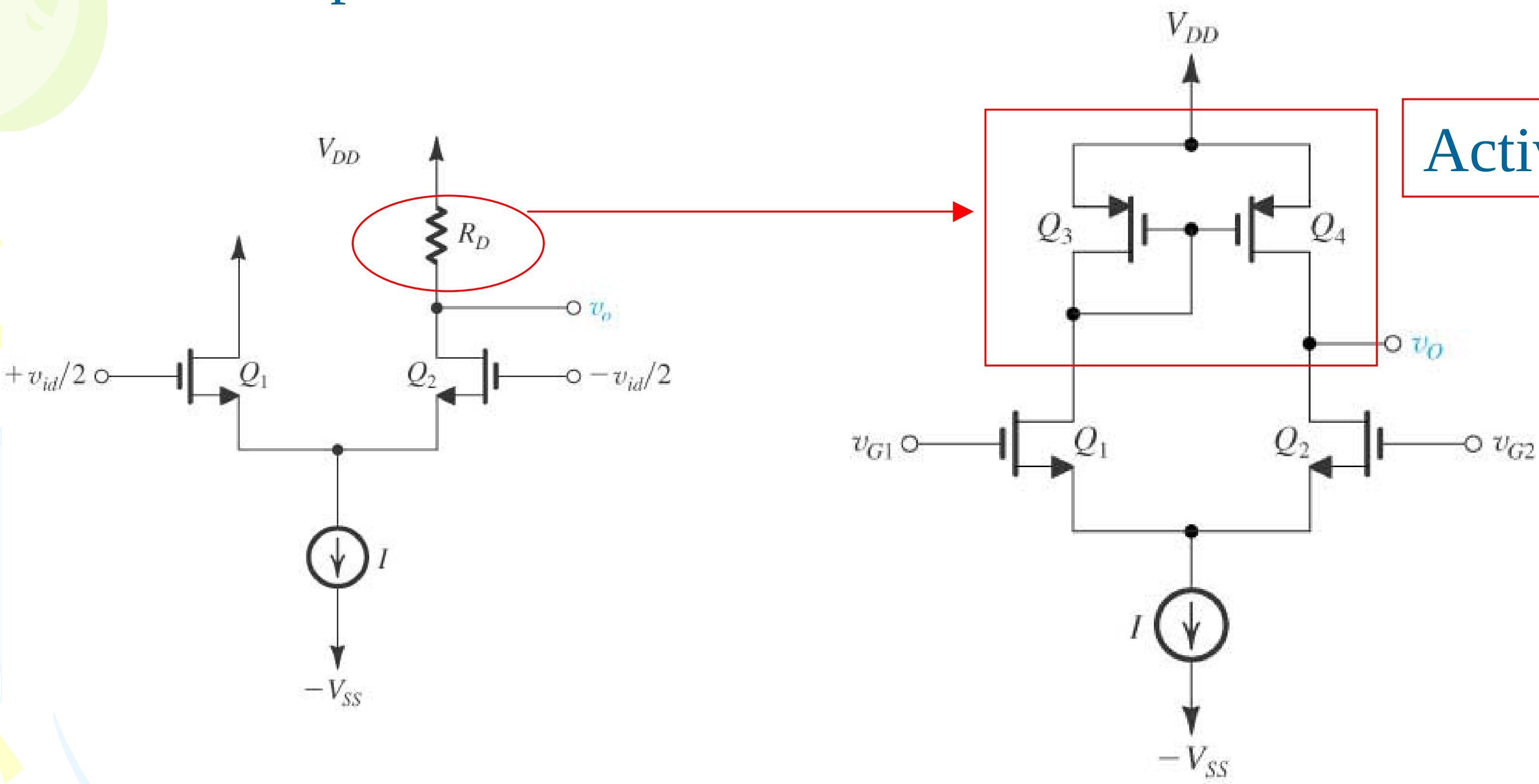
$$\frac{1}{2} k_n^{'} \frac{W}{L} (V_{GS} - V_t)^2 = \frac{I}{2}$$

$$\Delta I = \frac{I}{2} \frac{\Delta V_t}{V_{GS} - V_t} = \frac{I}{2} \frac{\Delta V_t}{V_{OV}}$$

$$V_{os} = \Delta V_t$$

$$\boxed{V_{os} = \sqrt{(\frac{V_{OV}}{2} \frac{\Delta R_D}{R_D})^2 + (\frac{V_{OV}}{2} \frac{\Delta (W/L)}{(W/L)})^2 + (\Delta V_t)^2}}$$

Differential amplifier with active load

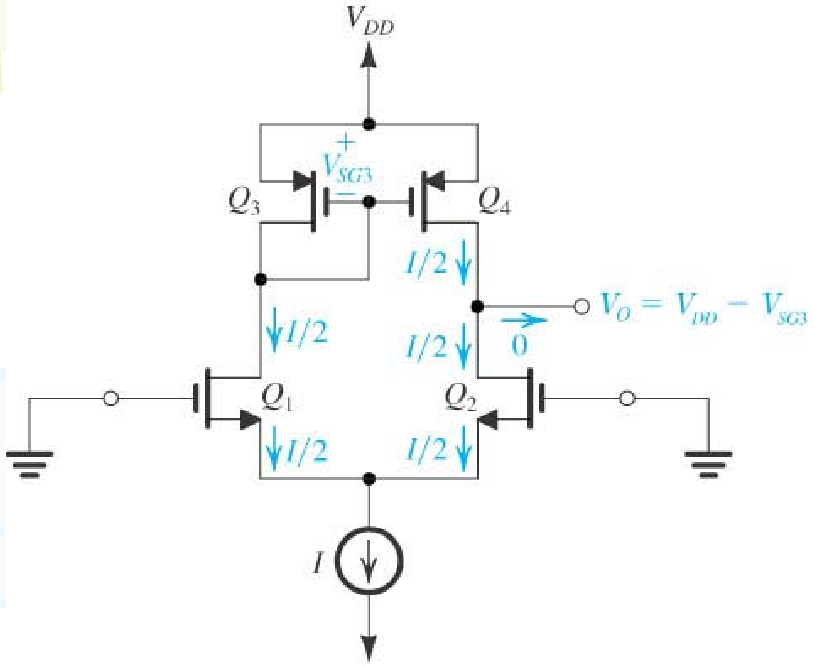


(a)

Active load

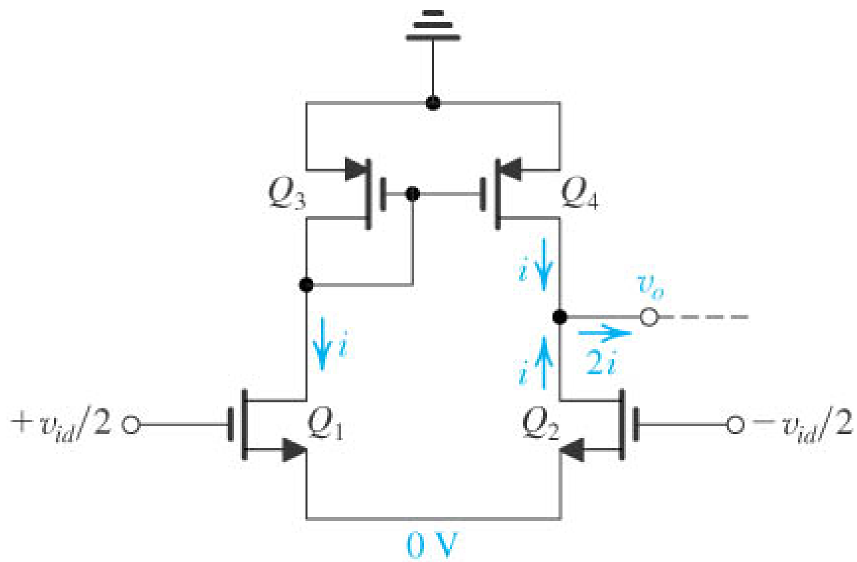
Improving:

1. Differential gain
2. Common-mode gain et CMRR
3. Input offset voltage



V_{DD}
V_{SG3}
Q_3
Q_4
$I/2$
$I/2$
$I/2$
$I/2$
$I/2$
$I/2$
$V_O = V_{DD} - V_{SG3}$
0
Q_1
Q_2
I

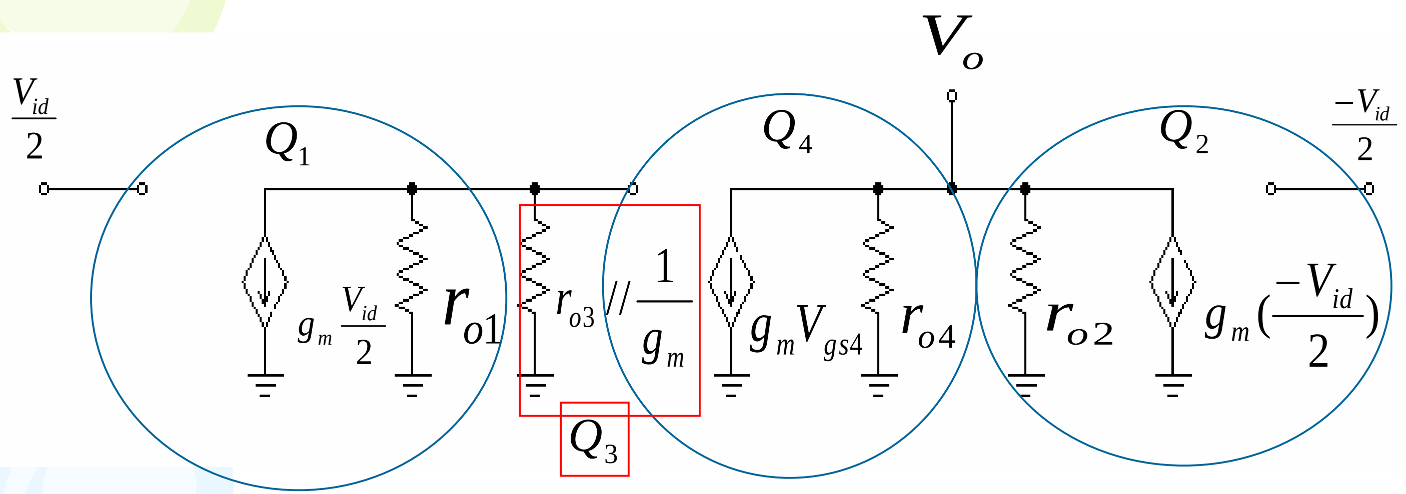
(b)

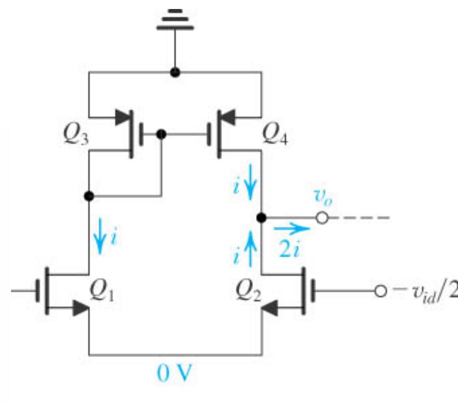


Q_3
Q_4
i
i
i
v_o
$2i$
$+v_{id}/2$
Q_1
Q_2
$-v_{id}/2$
0 V

(c)

Differential-mode equivalent circuit with active load





(c)

$$R_o = r_{o2} // r_{o4}$$

active load

$$R_o = r_o = R_{SS}$$

Passive load

$$v_o = -g_m\left(\tfrac{-v_{id}}{2} + v_{gs4}\right)(r_{o2} // r_{o4})$$

$$v_{gs4} = -g_m \tfrac{v_{id}}{2}\left(r_{o1} // r_{o3} // \frac{1}{g_m}\right) \approx -g_m \tfrac{v_{id}}{2}\frac{1}{g_m} = -\tfrac{v_{id}}{2}$$

$$A_d \equiv \frac{v_o}{v_{id}} = \frac{-g_m\left(\tfrac{-v_{id}}{2} + \tfrac{-v_{id}}{2}\right)(r_{o2} // r_{o4})}{v_{id}} = g_m(r_{o2} // r_{o4})$$

$when \quad r_{o2} = r_{o4} = r_o$

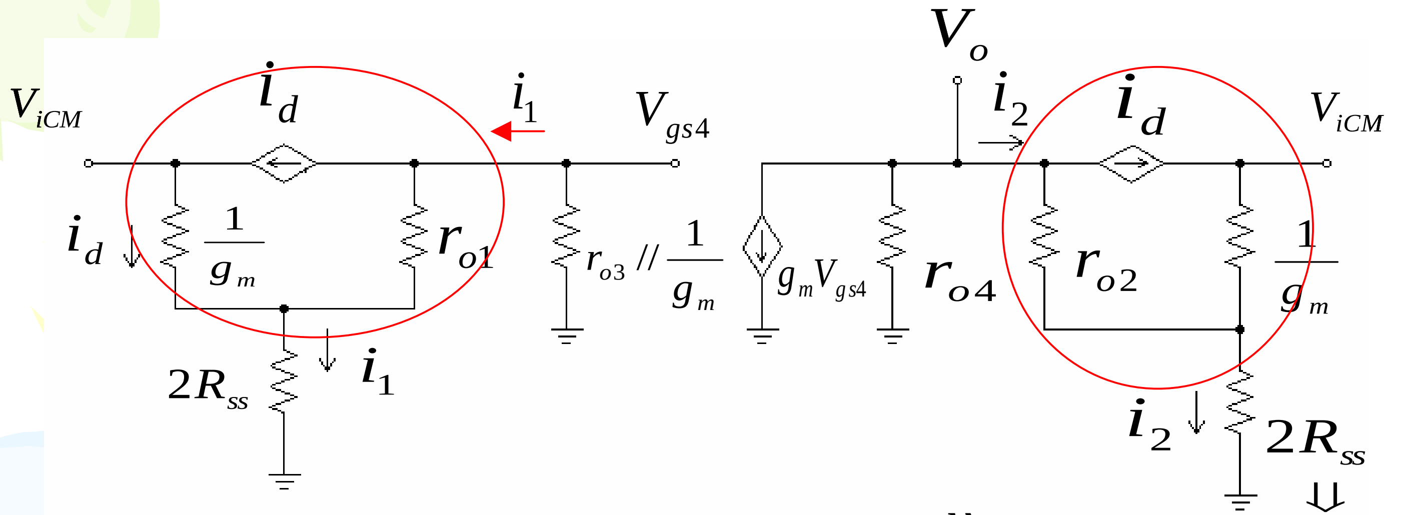
active load

$$A_d = \frac{g_m}{2} r_o$$

Passive load

$$A_d = g_m(R_D // r_o)$$

Common-mode equivalent circuit with active load



$(R_{ss} \approx r_o)$

$$v_o = -r_{o4}(g_m v_{gs4} + i_2)$$

$$v_{gs4} = -i_1 (r_{o4} // \frac{1}{g_m})$$

$$v_{icm} \approx i_1 2R_{SS}$$

$$v_{icm} \approx i_2 2R_{SS}$$

$$v_o = -r_{o4}(g_m v_{gs4} + \frac{v_{icm}}{2R_{SS}})$$

$$v_{gs4} = -\frac{v_{icm}}{2R_{SS}}(r_{o3} // \frac{1}{g_m})$$

$$v_o = -r_{o4}[-\frac{g_m v_{icm}}{2R_{SS}}(r_{o3} // \frac{1}{g_m}) + \frac{v_{icm}}{2R_{SS}}]$$

$$A_{cm} = \frac{v_o}{v_{icm}} = -\frac{r_{o4}}{2R_{SS}} \frac{1}{1 + r_{o3} g_m}$$

1. Find the transconductance G_m

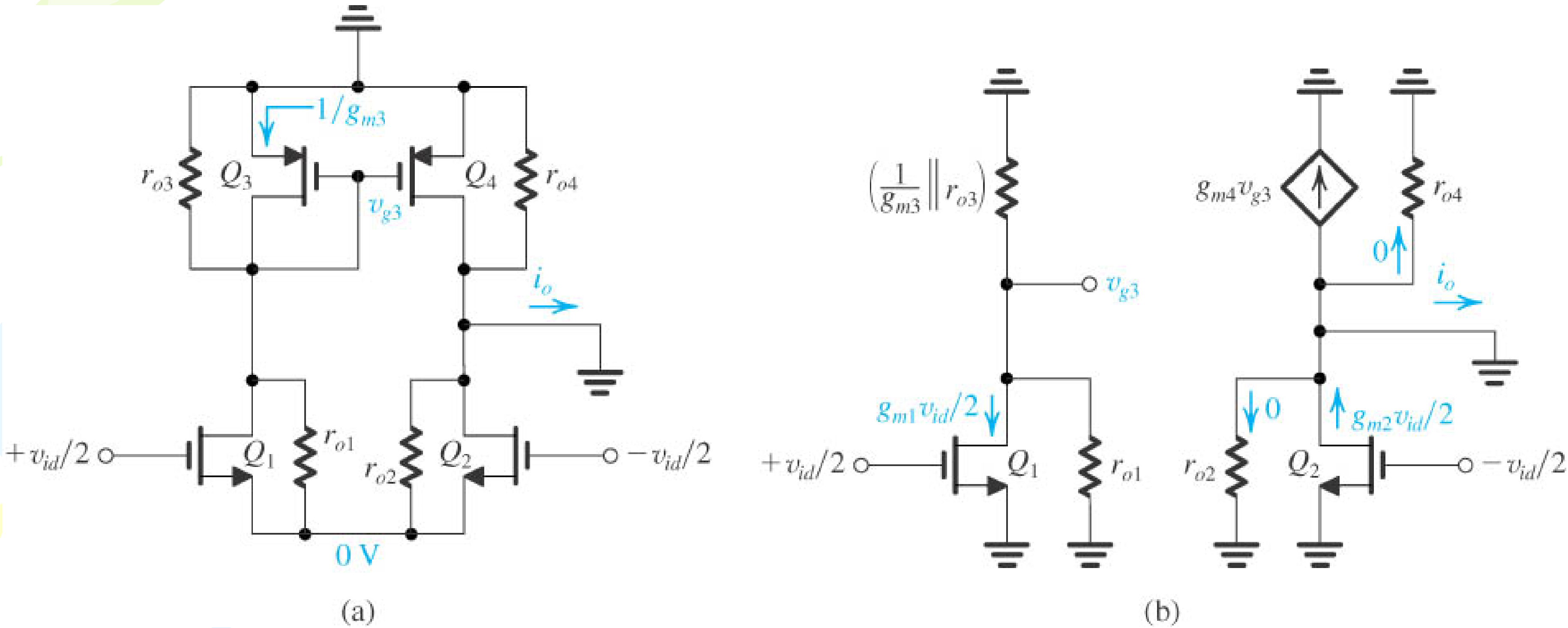
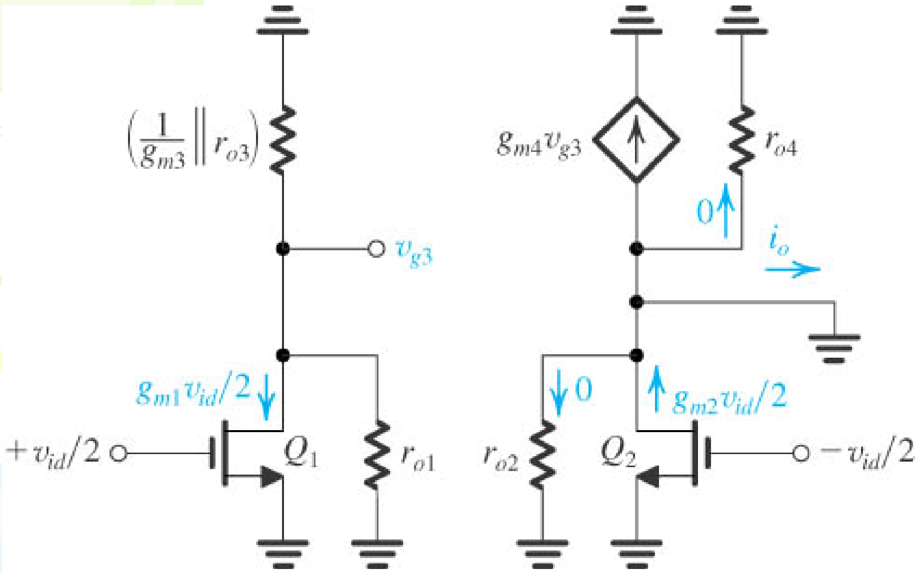


Figure 7.29 Determining the short-circuit transconductance G_m ; i_o/v_{id} of the active-loaded MOS differential pair.



(b)

$$v_{g3} = -g_{m1}\left(\frac{v_{id}}{2}\right)\left(\frac{1}{g_{m3}} // r_{o3} // r_{o1}\right)$$

$$r_{o1}, r_{o3} >> (1/g_{m3})$$

$$v_{g3} \approx -\frac{g_{m1}}{g_{m3}}\left(\frac{v_{id}}{2}\right)$$

$$i_o = -g_{m4}v_{g3} + g_{m2}\left(\frac{v_{id}}{2}\right)$$

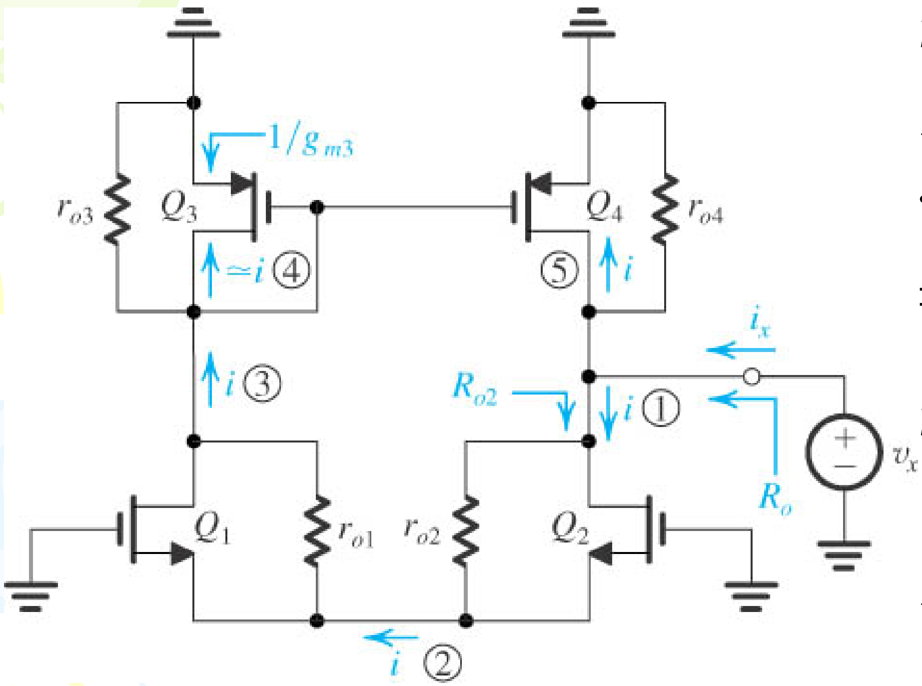
$$i_o = -g_{m1}\left(\frac{g_{m4}}{g_{m3}}\right)\left(\frac{v_{id}}{2}\right) + g_{m2}\left(\frac{v_{id}}{2}\right)$$

$$\because g_{m3} = g_{m4}, g_{m1} = g_{m2} = g_m$$

$$i_o = g_m v_{id}$$

$$G_m = g_m$$

2. Find the output resistance R_o



$$i = v_x / R_{o2}$$

$$R_{o2} = r_{o2} + (1 + g_{m2} r_{o2})(1/g_{m1})$$

$$\because g_{m2} r_{o2} >> 1$$

$$\Rightarrow R_{o2} = 2 r_{o2}$$

$$i_x = i + i + \frac{v_x}{r_{o4}} = 2i + \frac{v_x}{r_{o4}} = 2\frac{v_x}{R_{o2}} + \frac{v_x}{r_{o4}}$$

$$R_o \equiv \frac{v_x}{i_x} = r_{o2} // r_{o4}$$

3. Find the differential gain

$$A_d \equiv \frac{v_o}{v_{id}} = G_m R_o = g_m (r_{o2} // r_{o4})$$

$$when \quad r_{o2} = r_{o4} = r_o$$

$$A_d = \frac{g_m}{2} r_o$$

Common-mode gain et CMRR

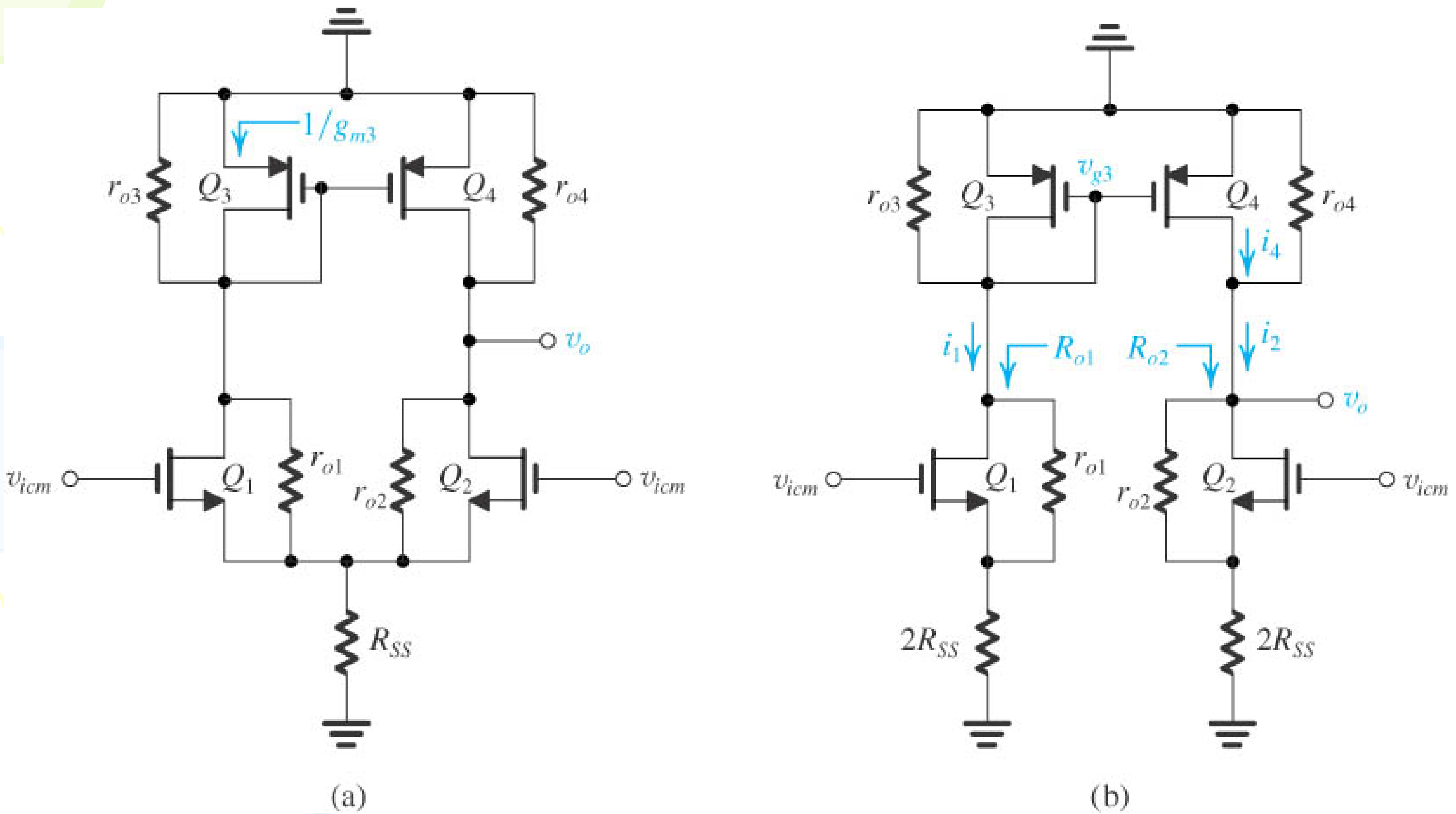
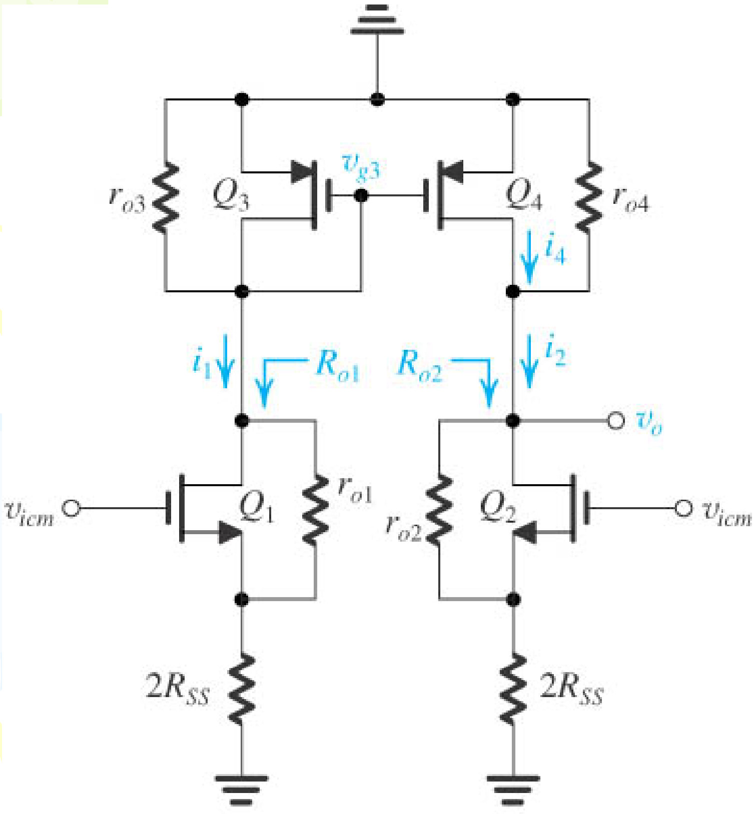


Figure 7.31 Analysis of the active-loaded MOS differential amplifier to determine its common-mode gain.



(b)

$$i_1 = i_2 \approx \frac{v_{icm}}{2R_{ss}}$$

$$R_{o1} = R_{o2} = r_o + 2R_{ss} + 2g_m r_o R_{ss}$$

$$v_{g3} = -i_1\left(\frac{1}{g_{m3}} // r_{o3}\right)$$

$$i_4 = -g_{m4}v_{g3} = g_{m4}i_1\left(\frac{1}{g_{m3}} // r_{o3}\right)$$

$$v_o = (i_4 - i_2)r_{o4} = [g_{m4}i_1\left(\frac{1}{g_{m3}} // r_{o3}\right) - i_2]r_{o4}$$

$$A_{cm} \equiv \frac{v_o}{v_{icm}} = -\frac{1}{2R_{ss}}\frac{r_{o4}}{1+g_{m3}r_{o3}}$$

$$\because g_{m3}r_{o3} >> 1, r_{o3} = r_{o4}$$

$$A_{cm} \approx -\frac{1}{2g_{m3}R_{ss}}$$

$$CMRR \equiv \left|\frac{A_d}{A_{cm}}\right| = [g_m(r_{o2} // r_{o4})][2g_{m3}R_{ss}]$$

$$let \quad r_{o2} = r_{o4} = r_o, g_{m3} = g_m$$

$$CMRR = g_m r_o g_m R_{ss}$$